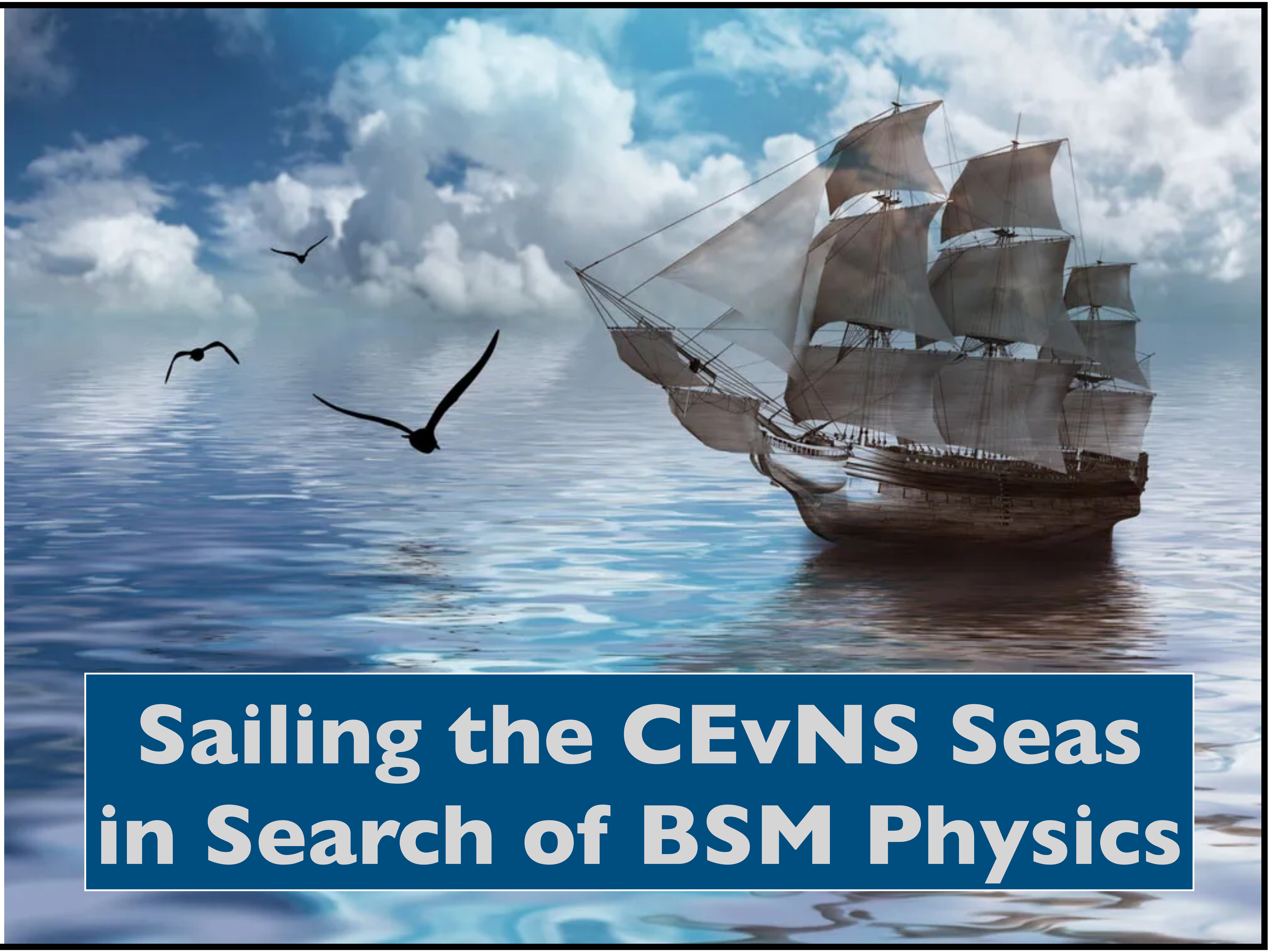
15th Conference on the Intersections of Particle & Nuclear Physics

June 12, 2025

Ian M. Shoemaker

VIRGINIA TECH



Sailing the CEvNS Seas in Search of BSM Physics

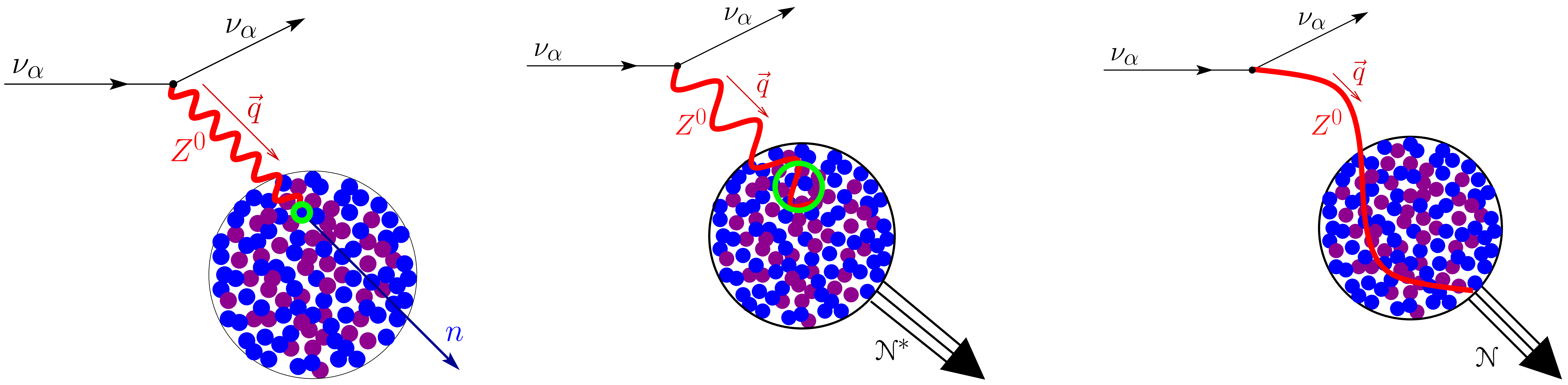
Outline

- CEvNS general features
- **Neutrino BSM**:
  - Non-Standard Neutrino Interactions (NSI) and CEvNS impact on matter effect.
  - CEvNS data can break degeneracies and provide non-trivial oscillation information.
- CEvNS experiments as **DM source**
  - Test high-priority models where DM yields the relic abundance.

CEvNS = Coherent Elastic Neutrino-Nucleus Scattering

$$\boxed{\lambda_{Z^0} = h/|\vec{q}|}$$

Scattering of nucleons adds coherently when the neutrino energy is sufficiently small



Inelastic incoherent	Elastic incoherent	Elastic coherent (CEνNS)
$\lambda_{Z^0} \ll 2R$	$\lambda_{Z^0} \lesssim 2R$	$\lambda_{Z^0} \gtrsim 2R$

[Image: Cadeddu, Dordei, Giunti, Europhysics Letters, Volume 143, Number 3, year 2023 (EPL 143 34001)]

A Bold Prediction

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

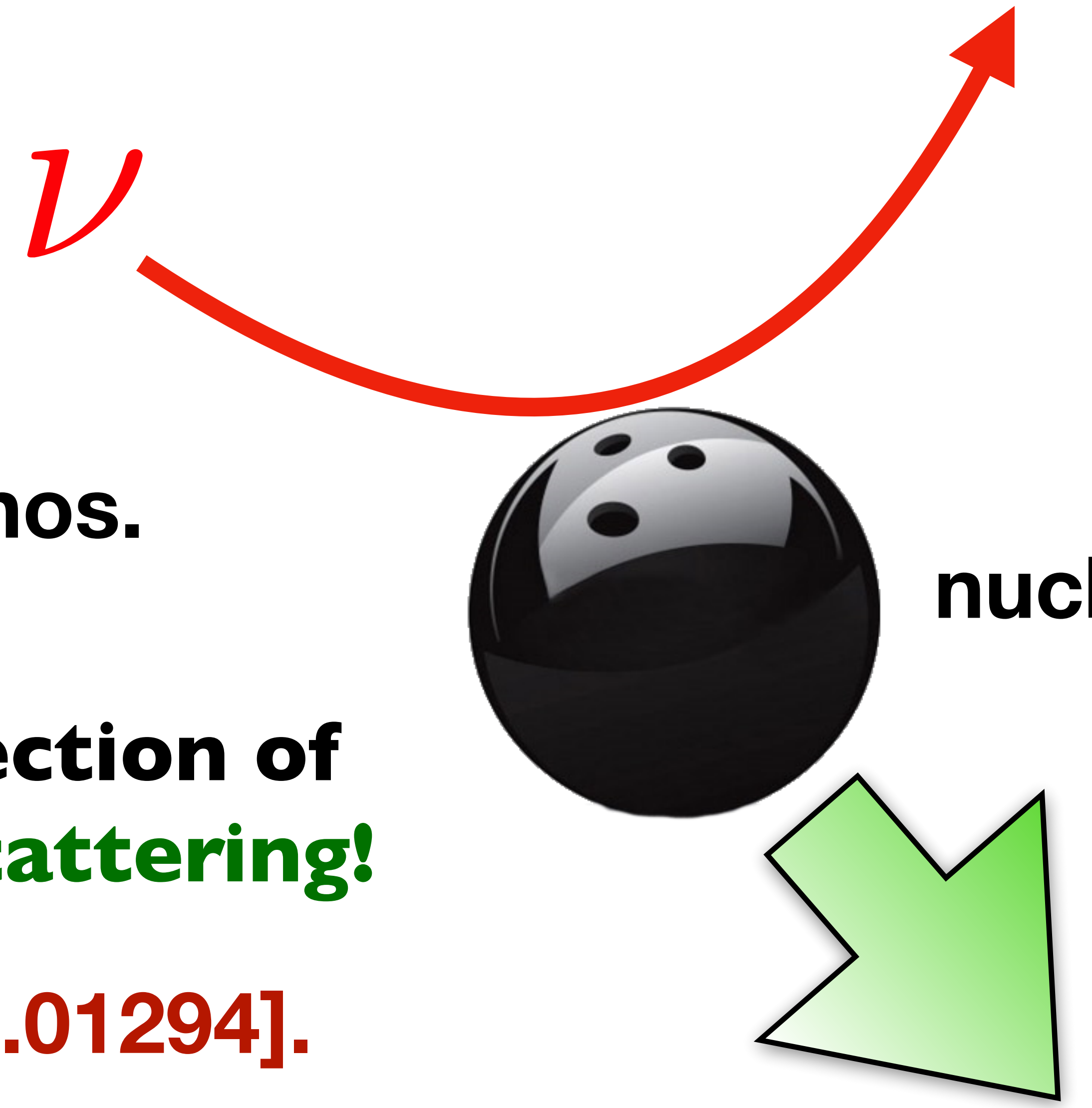
If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \rightarrow \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

*And independently by: V. B. Kopeliovich and L. L. Frankfurt

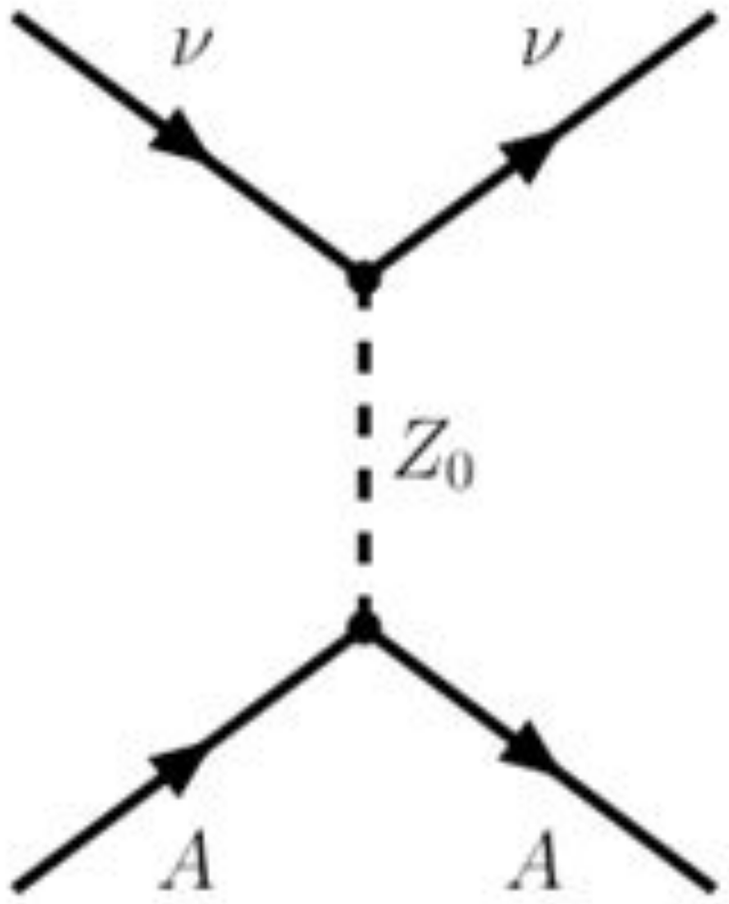
UW Madison
Ph.D. 1964

Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.

COHERENT Observation of CEvNS



$E_R \sim$ few keV

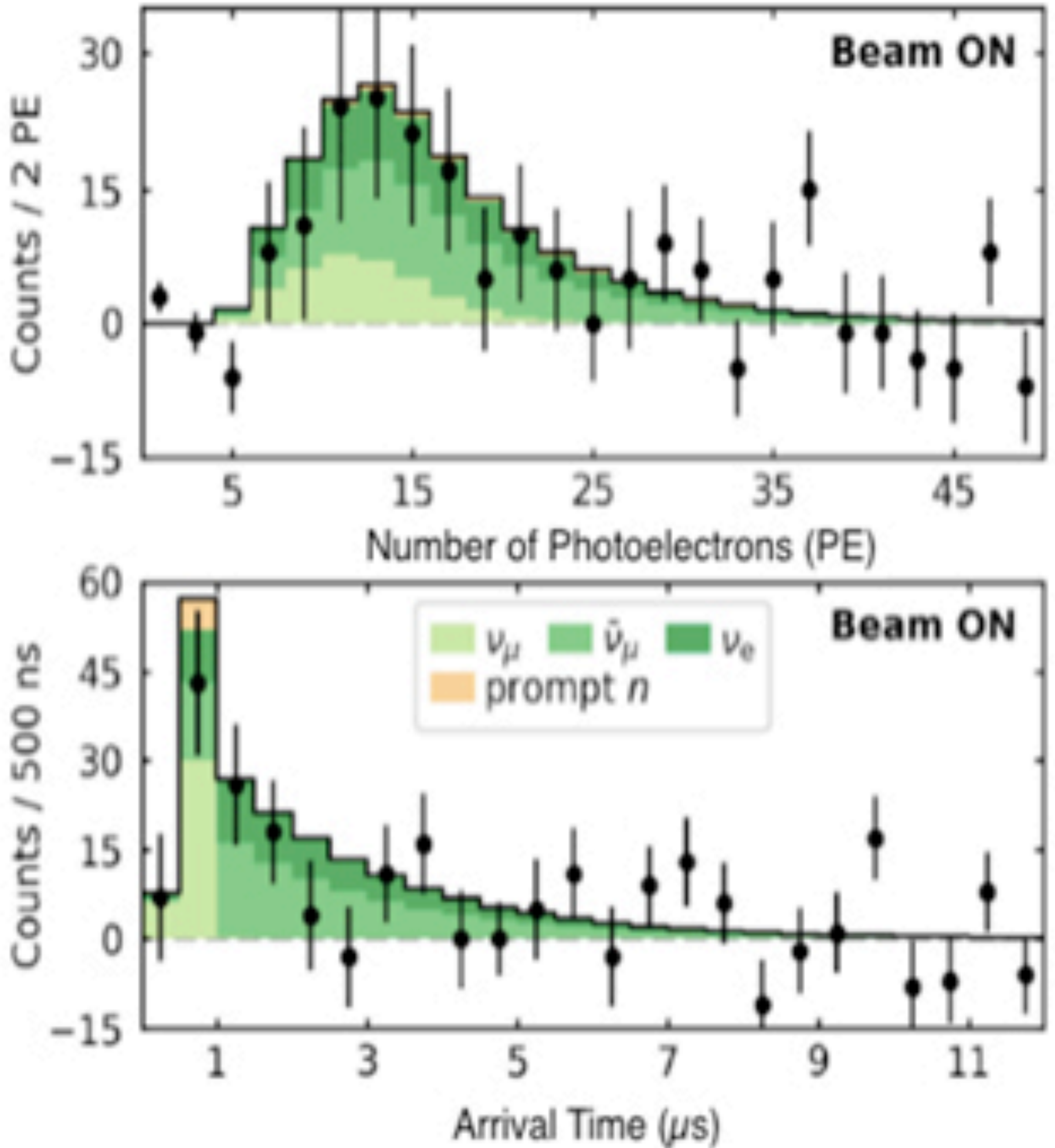


$$\sigma_{CE\nu NS} \propto N^2$$

Stopped pion source = low-E neutrinos.

COHERENT Collaboration: First detection of
Coherent Elastic Neutrino-Nucleus Scattering!

COHERENT Collaboration, 2017 [1708.01294].

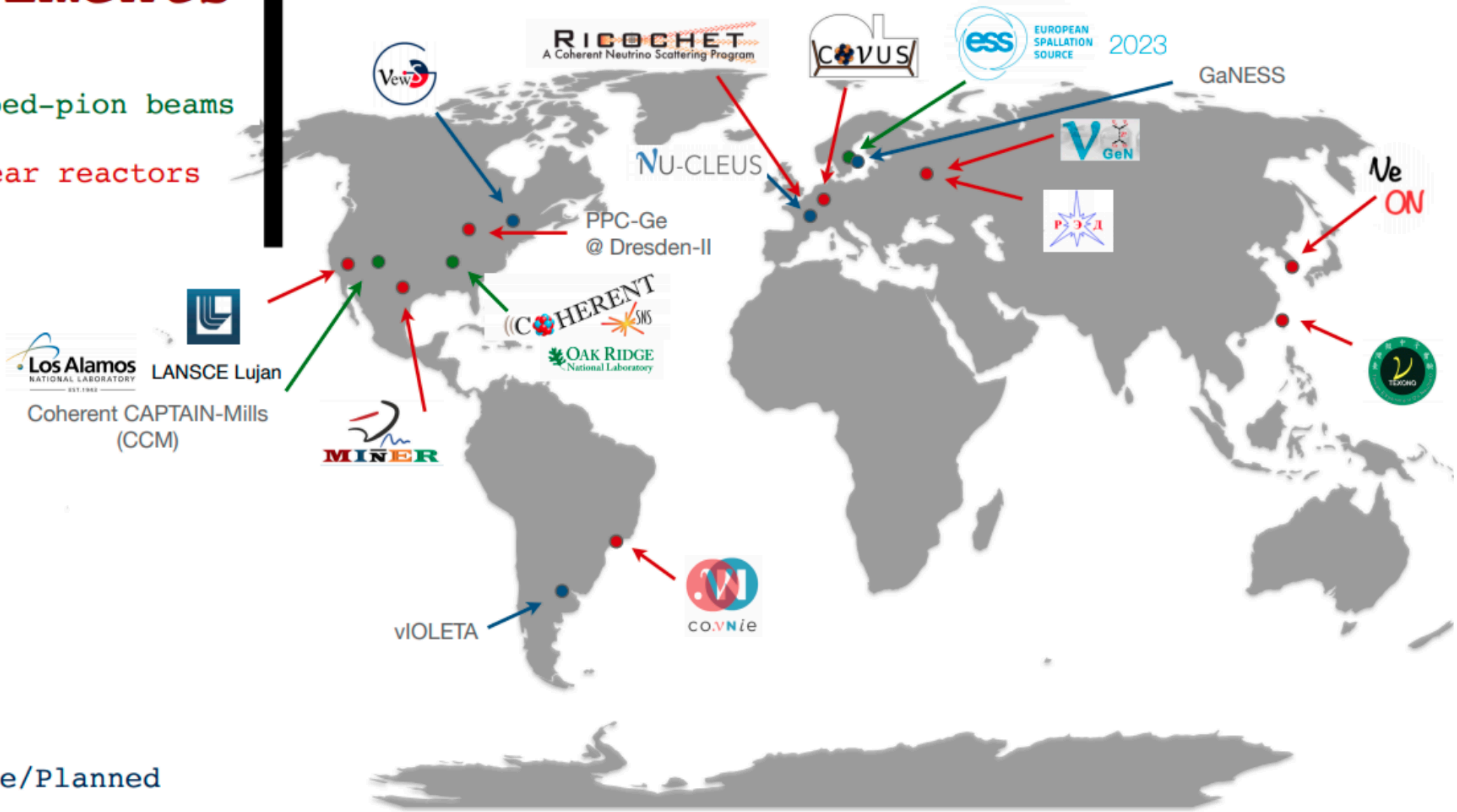


Rapid progress:

- LAr (2020).
- CsI update (2021)
- Ge (2024).

Experiments

- Stopped-pion beams
- Nuclear reactors

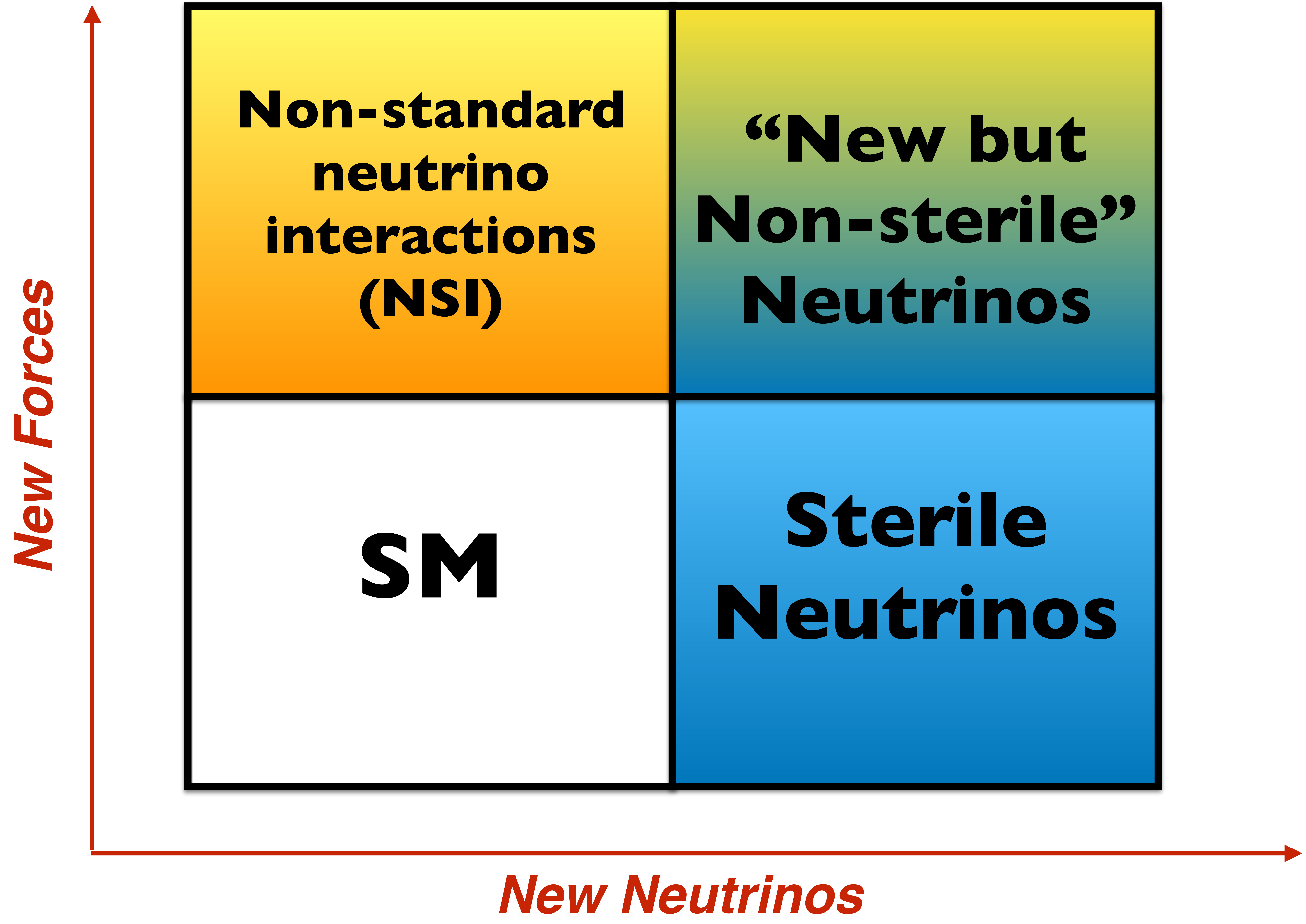


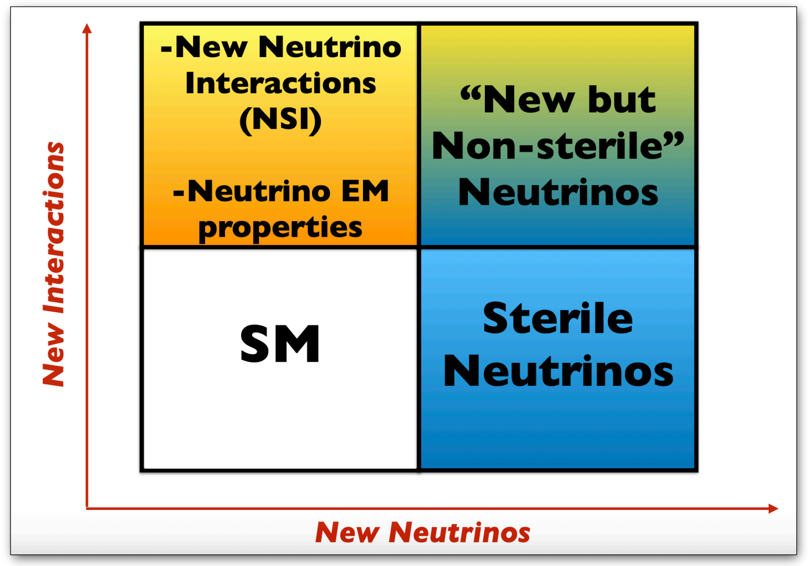
- Future/Planned

Credit to M. Green @Aspen 2019 Winter Conference

What can CEvNS do for BSM physics?

ν BSM Theory Landscape





ν-BSM Landscape @ CEνNS

An incomplete sample:

Sterile Neutrinos: Kosmas, Papoulias, Tortola, Valle [1703.00054]; De Romeri, Miranda, Papoulias, Sanchez Garcia, Tórtola, Valle [2211.11905]

New Interactions:

NSI: Barranco, Miranda, Rashba [hep-ph/0508299], Scholberg [hep-ex/0511042], Liao, Marfatia [1708.04255], IMS[1703.05774], Coloma, Denton, Gonzalez-Garcia, Maltoni, Schwetz [1701.04828]; Denton, Farzan IMS [1804.03660]; Link, Xu [1903.09891]; Denton, Gehrlein [2008.06062]; Chaves, Schwetz [2102.11981]; Coloma, Esteban, Gonzalez-Garcia, Larizgoitia, Monrabal, Palomares-Ruiz [2202.10829] ;V. De Romeri, O. G. Miranda, D. K. Papoulias, G. Sanchez Garcia, M. Tórtola, J. W. F. Valle [2211.11905], Coloma, Gonzalez-Garcia, Maltoni, Pinheiro, Urrea [2305.07698]

EM Properties: Cadeddu, Giunti, Kouzakov, Li, Studenikin, and Zhang [1810.05606]; Cadeddu, Dordei, Giunti, Li, Picciau, Zhang [2005.01645]; V. De Romeri, O. G. Miranda, D. K. Papoulias, G. Sanchez Garcia, M. Tórtola, J. W. F. Valle [2211.11905], De Romeri, Papoulias, Sanchez Garcia, Ternes, Tortola [2412.14991]

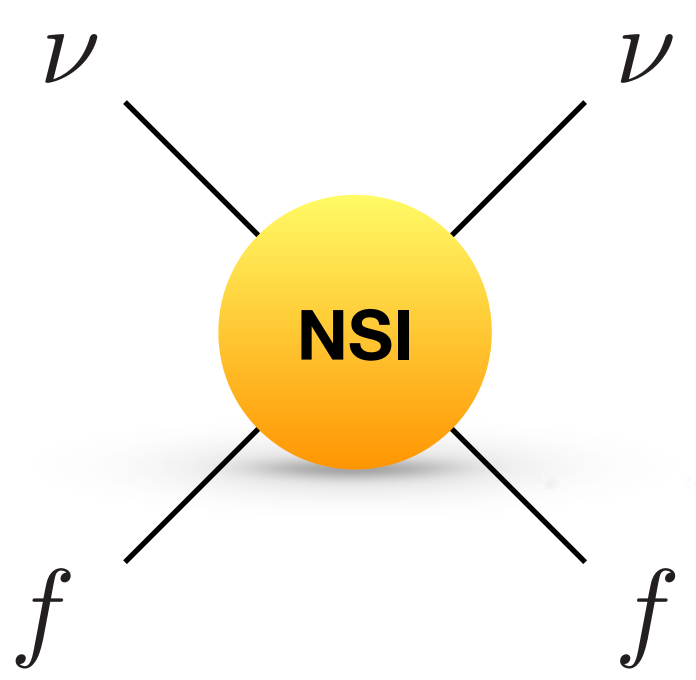
"Sterile" + New Interactions:

Dipole portal: Dasgupta, Kang, Kim [2108.12998]; Bolton, Deppisch, Fridell, Harz, Hati, Kulkarni [2110.02233] ;Aristizabal, De Romeri, Papoulias [2203.02414], De Romeri, Papoulias, Sanchez Garcia, Ternes, Tórtola [2412.14991].

Neutrino-DM conversion: Brdar, Rodejohann, Xu [1810.03626], Hurtado, Mir, IMS, Welch, Wyenberg [2005.13384], Candela, De Romeri, Papaoulias [2305.03341]

EFT with Steriles Li, Ma, Schmidt [2005.01543].

Matter really Matters



Neutrino oscillations in matter

L. Wolfenstein

Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\,\epsilon^{fP}_{\alpha\beta}(\overline{\nu}_\alpha\gamma^\rho\nu_\beta)(\overline{f}\gamma_\rho P f)$$

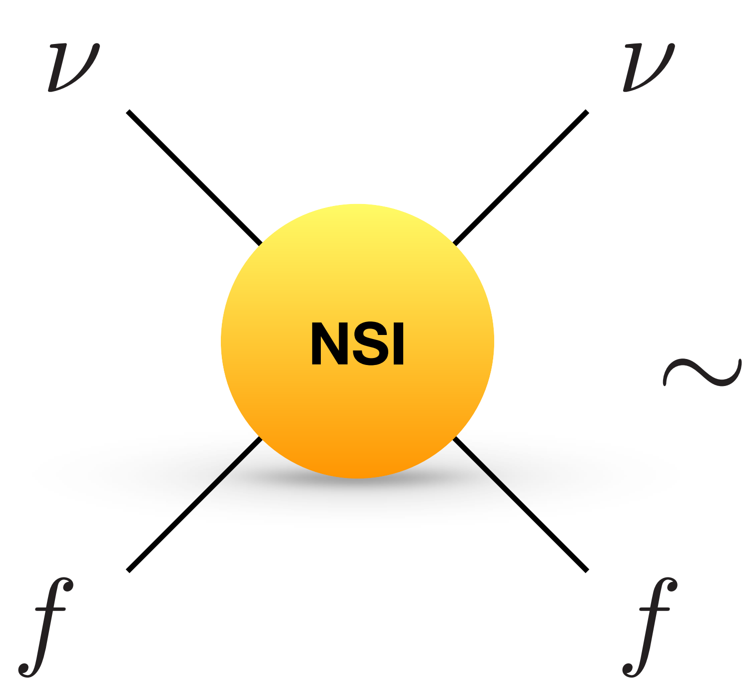
Neutrino Flavor

f =SM fermion
P=L,R

- **Coherent forward scattering** crucial for neutrino oscillations.
- **Oscillation physics constrain neutrino-medium interactions.**

Oscillation Degeneracies

de Gouvea, Friedland, Murayama [hep-ph/0002064],
Miranda, Tortola, Valle [hep-ph/0406280],
Coloma, Schwetz [1604.05772]



$\sim \varepsilon \, G_F$

- Oscillation data allow large NSI in the "LMA-dark" window.

standard osc.

$$\theta_{12} \simeq 34^\circ$$

osc. degenerate ⟷

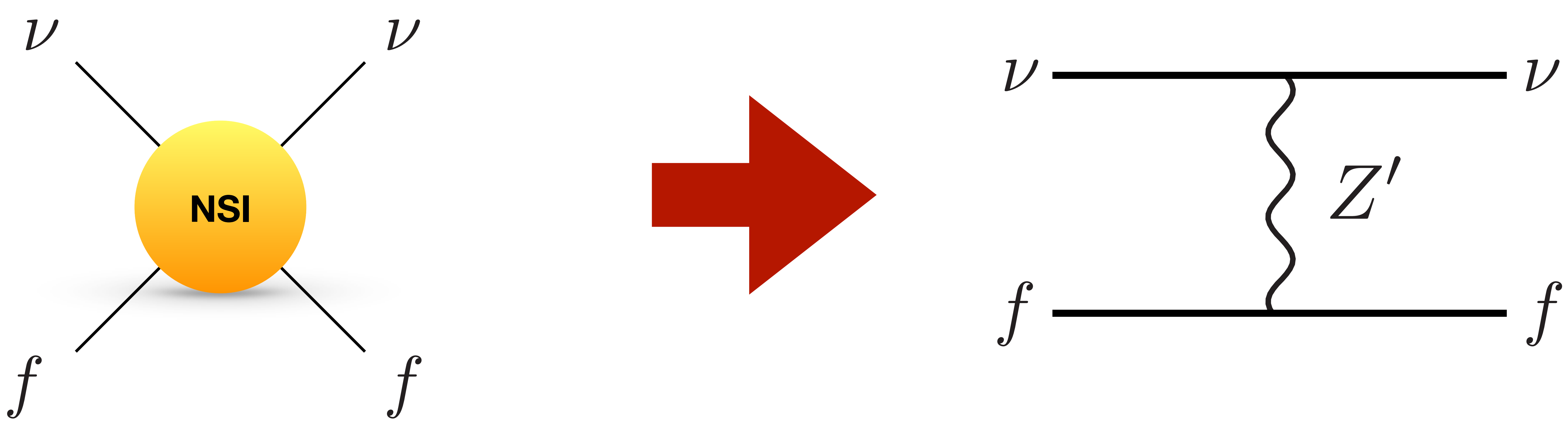
LMA-dark

$$45^\circ < \theta_{12} < 90^\circ$$

$$+ \ \varepsilon \sim \mathcal{O}(1)$$

Scattering data can break this degeneracy.

NSI at low masses



$$\varepsilon \, G_F \sim \frac{g^2}{m_{Z'}^2}$$

- **Various models on the market involving gauge B & L combinations and/or introducing heavy sterile neutrinos.**

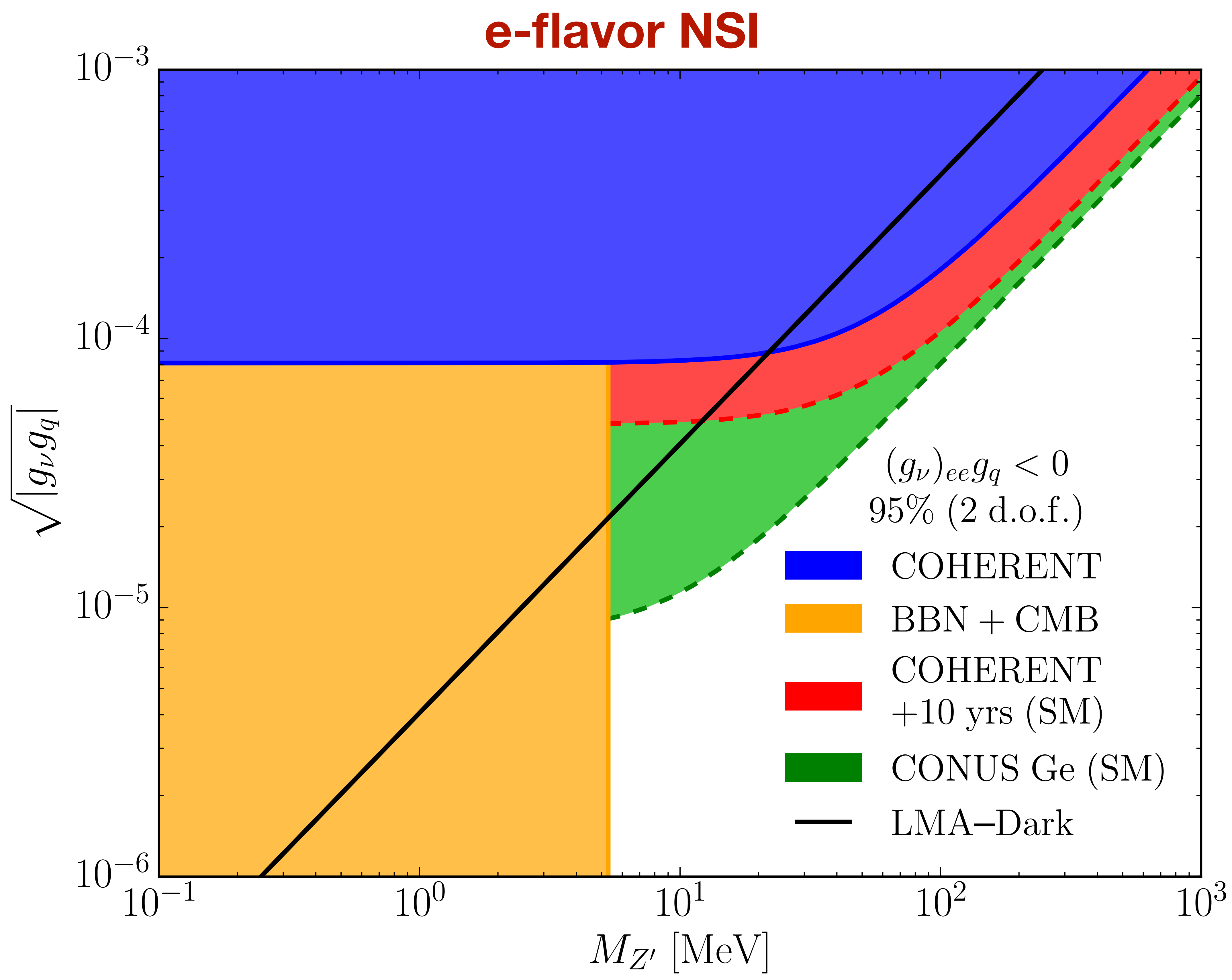
[Farzan (2015)], [IMS, Farzan (2015)], [Babu, Friedland, Machado, Mocioiu (2017), [Denton, Farzan, IMS (2018)], ...

NSI at low masses

Denton, Farzan, IMS [JHEP 2018]

COHERENT sees:

$$\frac{d\sigma^{\rm NSI}}{dE_R} \propto \begin{cases} \frac{g_\nu^2 g_q^2 m_N}{m_{Z'}^4} & \text{if } m_{Z'} \gg q, \\ \frac{g_\nu^2 g_q^2 m_N}{q^4} & \text{if } m_{Z'} \ll q. \end{cases}$$



Oscillation sees:

$$V_{\rm matt} = \frac{g_\nu g_q}{m_{Z'}^2} n_f.$$

For more viable LMA-D scenarios see: Coloma, Gonzalez-Garcia, Maltoni [2009.14220]; Chaves, Schwetz [2102.11981], Denton, Gehrlein [2204.09060]

- **At the time allowed for a narrow viable range for LMA-Dark, ruled out now by Dresden-II for e-type NSI (Denton, Gehrlein [2204.09060]).**

New CEvNS data from the Solar Nu's @ DM experiments

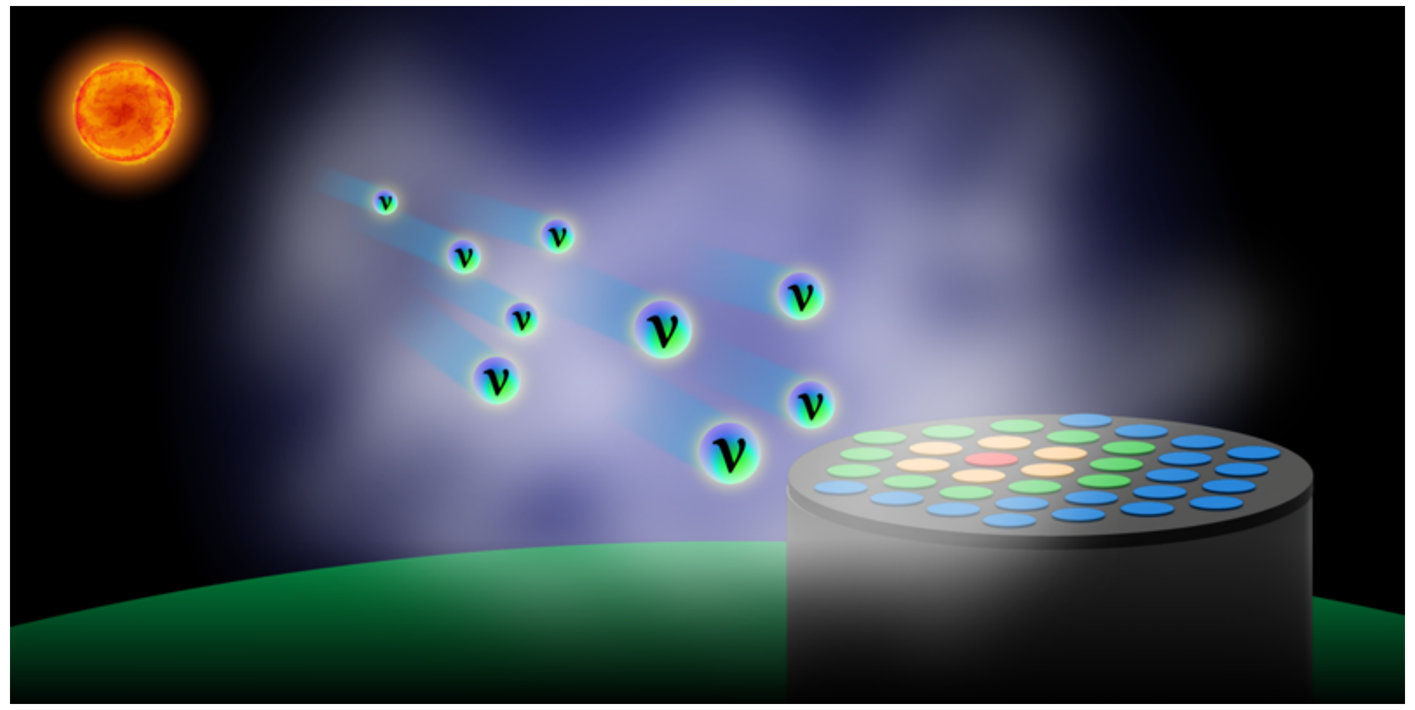


Image: APS/Alan Stonebraker

PHYSICAL REVIEW LETTERS 133, 191002 (2024)

Editors' Suggestion | Featured in Physics

First Indication of Solar ^{8}B Neutrinos via Coherent Elastic Neutrino-Nucleus Scattering with XENONnT

E. Aprile,[1] J. Aalbers,[2] K. Abe,[3] S. Ahmed Maouloud,[4] L. Althueser,[5] B. Andrieu,[4] E. Angelino,[6,7] D. Antón Martin,[8] F. Arneodo,[9] L. Baudis,[10] M. Bazyk,[11] L. Bellagamba,[12] R. Biondi,[13] A. Bismark,[10] K. Boese,[13] A. Brown,[14] G. Bruno,[11] R. Budnik,[15] C. Cai,[16] C. Capelli,[10] J. M. R. Cardoso,[17] A. P. Cimental Chávez,[10] A. P. Colijn,[18] J. Conrad,[19] J. J. Cuenca-García,[10] V. D'Andrea,[7,*] L. C. Daniel Garcia,[4] M. P. Decowski,[18] A. Deisting,[20] C. Di Donato,[21,7] P. Di Gangi,[12] S. Diglio,[11] K. Eitel,[22] A. Elykov,[22] A. D. Ferella,[21,7] C. Ferrari,[7] H. Fischer,[14] T. Flehmke,[19] M. Flierman,[18] W. Fulgione,[6,7] C. Fuselli,[18] P. Gaemers,[18] R. Gaior,[4] M. Galloway,[10] F. Gao,[16] S. Ghosh,[23] R. Giacomobono,[24] R. Glade-Beucke,[14] L. Grandi,[8] J. Grigat,[14] H. Guan,[23] M. Guida,[13] P. Gyorgy,[20] R. Hammann,[13] A. Higuera,[25] C. Hils,[20] L. Hoetzsch,[13] N. F. Hood,[26] M. Iacovacci,[24] Y. Itow,[27] J. Jakob,[5] F. Joerg,[13,10] Y. Kaminaga,[3] M. Kara,[22] P. Kavrigin,[15] S. Kazama,[27] M. Kobayashi,[27] D. Koke,[5] A. Kopec,[26,†] F. Kuger,[14] H. Landsman,[15] R. F. Lang,[23] L. Levinson,[15] I. Li,[25] S. Li,[28] S. Liang,[25] Y.-T. Lin,[13] S. Lindemann,[14] M. Lindner,[13] K. Liu,[16,‡] M. Liu,[1,16] J. Loizeau,[11] F. Lombardi,[20] J. Long,[8] J. A. M. Lopes,[17,§] T. Luce,[14] Y. Ma,[26] C. Macolino,[21,7] J. Mahlstedt,[19] A. Mancuso,[12] L. Manenti,[9] F. Marignetti,[24] T. Marrodán Undagoitia,[13] K. Martens,[3] J. Masbou,[11] E. Masson,[4] S. Mastroianni,[24] A. Melchiorre,[21,7] J. Merz,[20] M. Messina,[7] A. Michael,[5] K. Miuchi,[29] A. Molinario,[6] S. Moriyama,[3] K. Morå,[1] Y. Mosbacher,[15] M. Murra,[1] J. Müller,[14] K. Ni,[26] U. Oberlack,[20] B. Paetsch,[15] Y. Pan,[4] Q. Pellegrini,[4] R. Peres,[10] C. Peters,[25] J. Pienaar,[8,15] M. Pierre,[18] G. Plante,[1] T. R. Pollmann,[18] L. Principe,[11] J. Qi,[26] J. Qin,[25] D. Ramírez García ... L. Sanchez,[25] J. M. F. dos Santos,[17] I. Sarnoff,[9] G. Sartorelli,[12] J. Schreiner,[13] P. ... M. Schumann,[14] L. Scotto Lavina,[4] M. Selvi,[12] F. Semeria,[12] P. Shagin,[20] ... H. Simgen,[13] A. Takeda,[3] P.-L. Tan,[19] D. Thers,[11] F. Toschi,[22] G. Trinchero,[6] ... K. Valerius,[22] S. Vecchi,[30] S. Vetter,[22] F. I. Villazon Solar,[20] G. Volta,[13] C. Weinhei... C. Wittweg,[10] V. H. S. Wu,[22] Y. Xing,[11] D. Xu,[1,‖] Z. Xu,[1] M. Yamashita,[3] L. ... G. Zavattini,[30] and M. Zhong[26]

(XENON Collaboration)

XENON

PANDA X

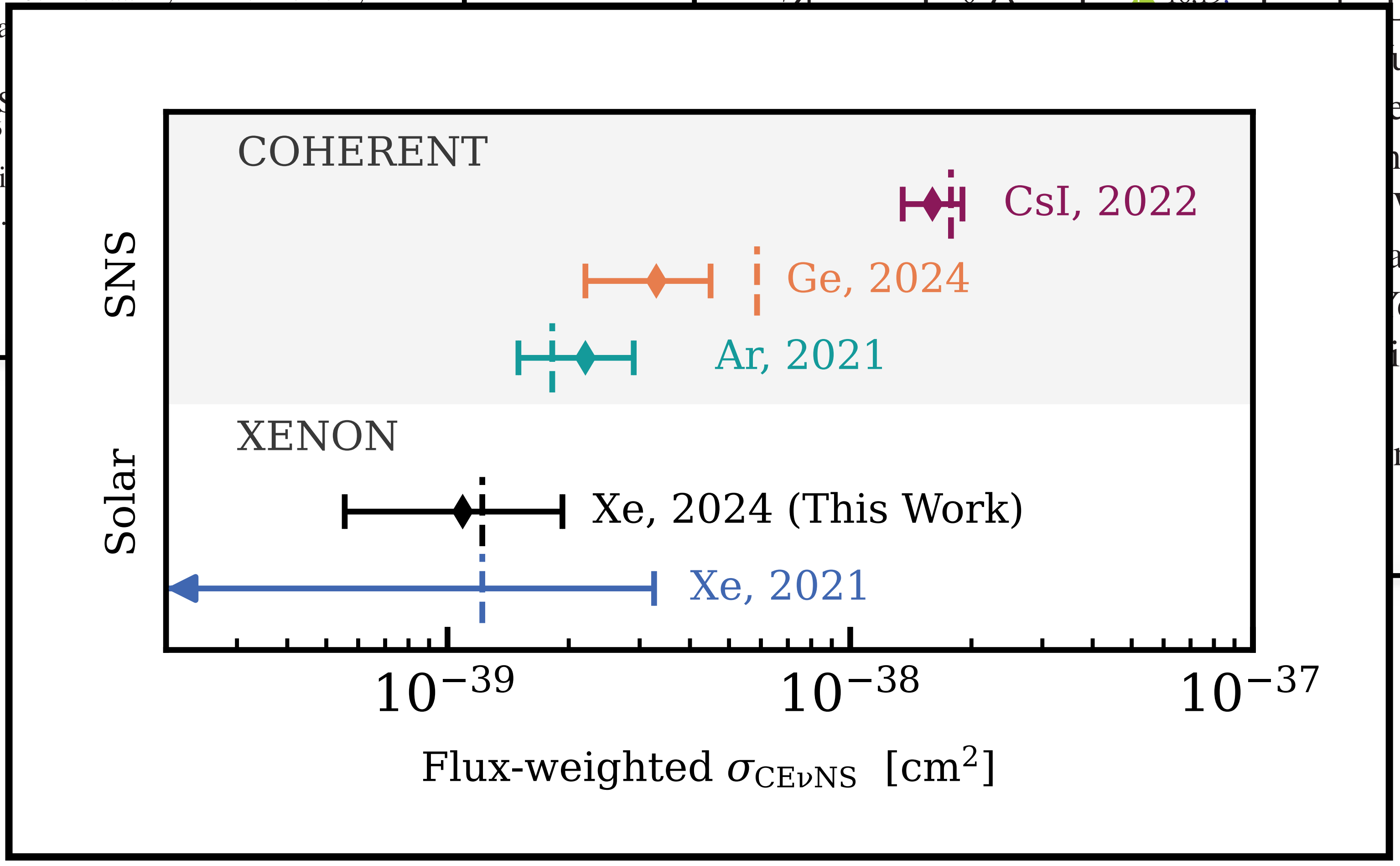
PHYSICAL REVIEW LETTERS 133, 191001 (2024)

Editors' Suggestion | Featured in Physics

First Indication of Solar ^{8}B Neutrinos through Coherent Elastic Neutrino-Nucleus Scattering in PandaX-4T

Zihao Bo,[2] Wei Chen,[2] Xun Chen,[1,2,3,4] Yunhua Chen,[5,4] Zhaokan Cheng,[6] Xiangyi Cui,[1] Yingjie Fan,[7] Deqing Fang,[8] Zhixing Gao,[2] Lisheng Geng,[9,10,11,12] Karl Giboni,[2,4] Xunan Guo,[9] Xuyuan Guo,[5,4] Zichao Guo,[9] Chencheng Han,[1] Ke Han,[2,4] Changda He,[2] Jinrong He,[5] Di Huang,[2] Houqi Huang,[13] Junting Huang,[2,4] Ruquan Hou,[3,4] Yu Hou,[14] Xiangdong Ji,[15] Xiangpan Ji,[16] Yonglin Ju,[14,4] Chenxiang Li,[2] Jiafu Li,[17] Mingchuan Li,[5,4] Shuaijie Li,[5,2,4] Tao Li,[6] ... Liu,[1,2,3,4,†] Congcong Lu,[14] Xiaoying Lu,[20,21] Lingyin Luo,[22] Yunyang Luo,[19] ...ue Meng,[2,3,4,‡] Xuyang Ning,[2] Binyu Pang,[20,21] Ningchun Qi,[5,4] Zhicheng Qian,[2] ...eng Shang,[2] Xiyuan Shao,[16] Guofang Shen,[9] Manbin Shen,[5,4] Wenliang Sun,[5,4] ...ng,[2] Hao Wang,[2] Jiamin Wang,[1] Lei Wang,[23] Meng Wang,[20,21] Qiuhong Wang,[8] ...Wei Wang,[6,17] Xiuli Wang,[14] Xu Wang,[1] Zhou Wang,[1,2,3,4] Yuehuan Wei,[6] ...ao,[2] Xiang Xiao,[17] Kaizhi Xiong,[5,4] Yifan Xu,[14] Shunyu Yao,[13] Binbin Yan,[1] ...e,[2] Chunxu Yu,[16] Ying Yuan,[2] Zhe Yuan,[8] Youhui Yun,[2] Xinning Zeng,[2] ...ibo Zhang,[1] Shu Zhang,[17] Tao Zhang,[1,2,3,4] Wei Zhang,[1] Yang Zhang,[20,21] ... Li Zhao,[1,2,3,4] Jifang Zhou,[5,4] Jiaxu Zhou,[13] Jiayi Zhou,[1] Ning Zhou,[1,2,3,4,§] ...ng Zhou,[9] Yubo Zhou,[2] and Zhizhen Zhou[2]

(PandaX Collaboration)



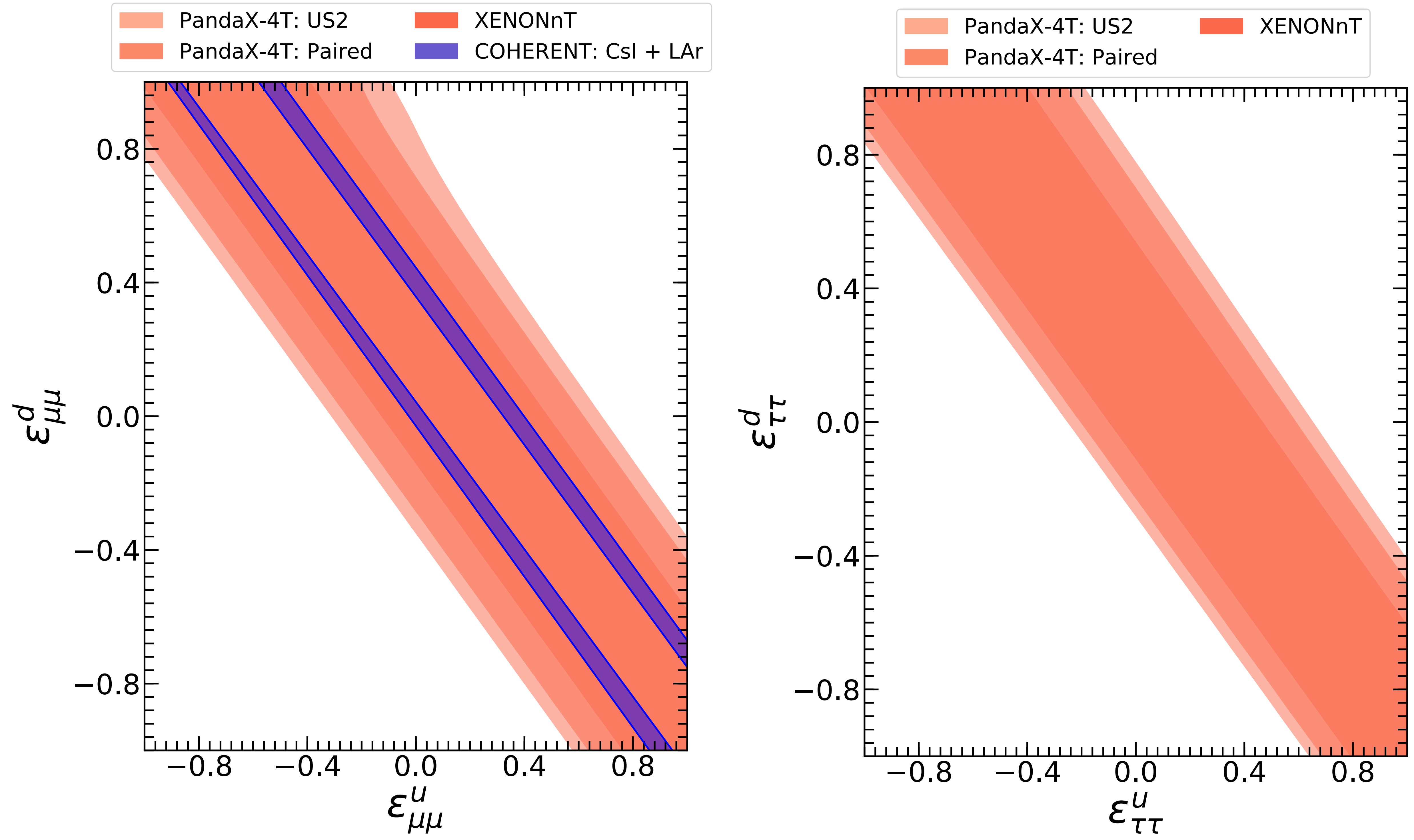
Background can become an interesting signal

NSI @ XENONnT & PandaX

NSI induces two effects:

(1) CEvNS modification in detector

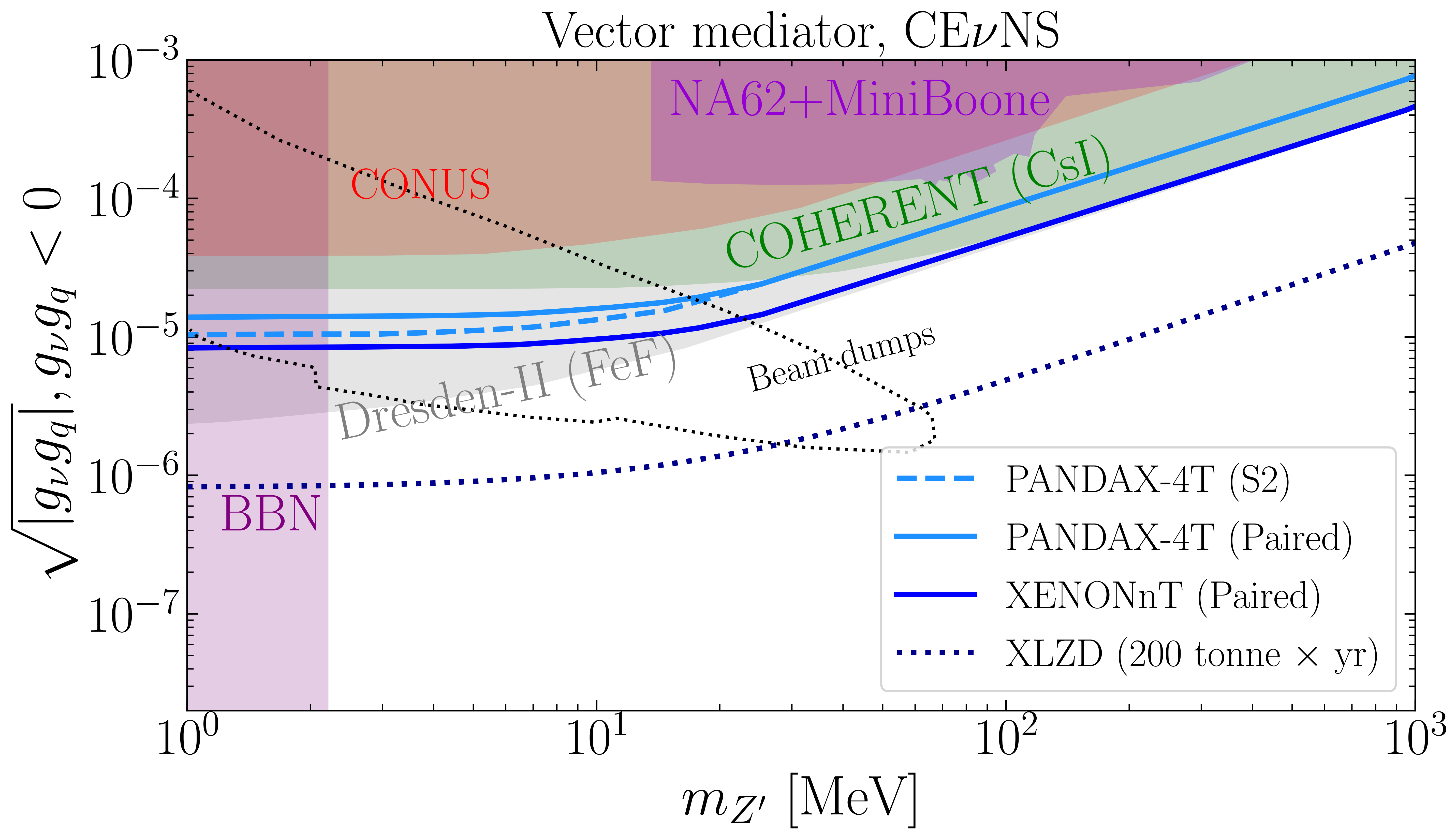
(2) NSI matter effect



Access to tau-flavor gives unique NSI probe at DM experiments.

- Sierra, Mishra, Strigari *Phys.Rev.D* 111 (2025) 5, 055007

Complimentary Light Mediator Bounds



PandaX S2 lower threshold implies better bounds than PandaX paired search at low masses.

Despite larger thresholds XENONnT wins at low-mass due to upward fluctuation in PandaX S2.

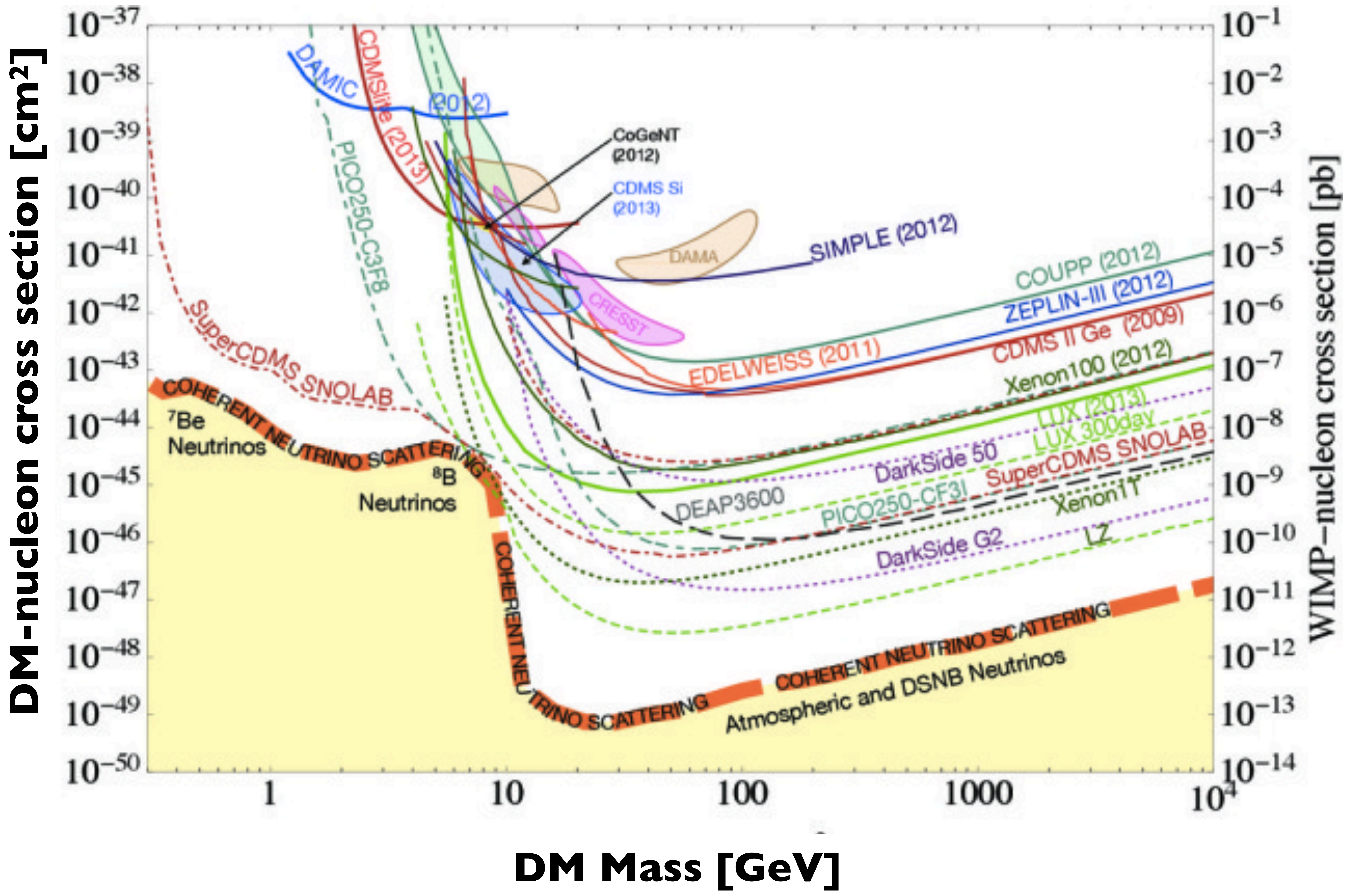
Blanco-Mas, Coloma, Herrera, Huber, Kopp, IMS, Tabrizi [2411.14206]

Important lesson:
Don't re-invent the wheel

↓

If Dark Matter experiments can be a tool for neutrino physics,
can neutrino experiments become a tool for DM?

DM Direct Detection



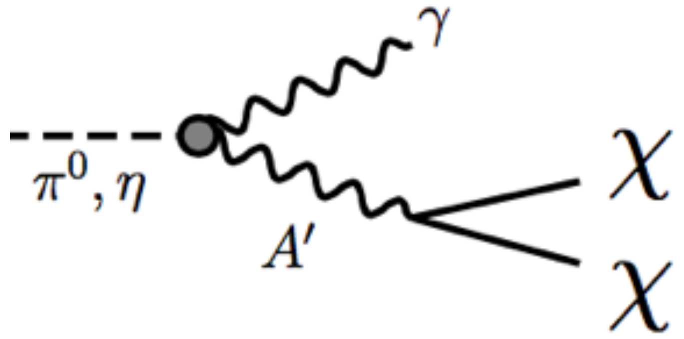
Very challenging to probe **sub-GeV Dark Matter** if you're stuck with galactic speeds (~200 km/s).

COHERENT Strategy for DM: make it

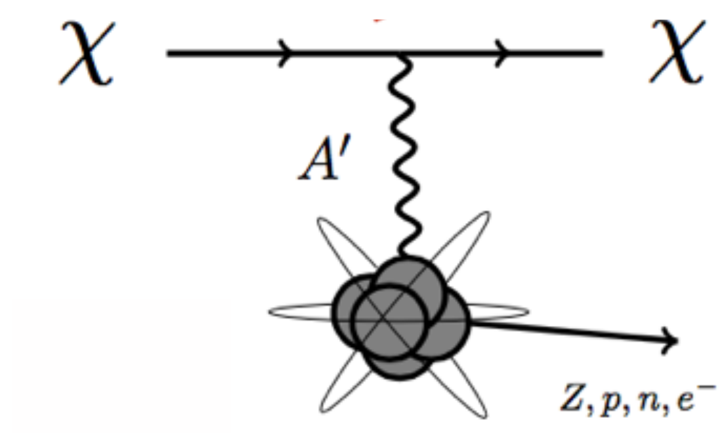
Batell, Pospelov, Ritz [0906.5614]
deNiverville, Pospelov, Ritz [1505.07805]
Shao-Feng Ge, IMS (JHEP 2018), ...

$$\mathcal{L} \supset \mathcal{L}_X - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{V'}V'^{\mu}V'_{\mu} - \epsilon F_{\mu\nu}F'^{\mu\nu}$$

COHERENT as a “dark matter beam”

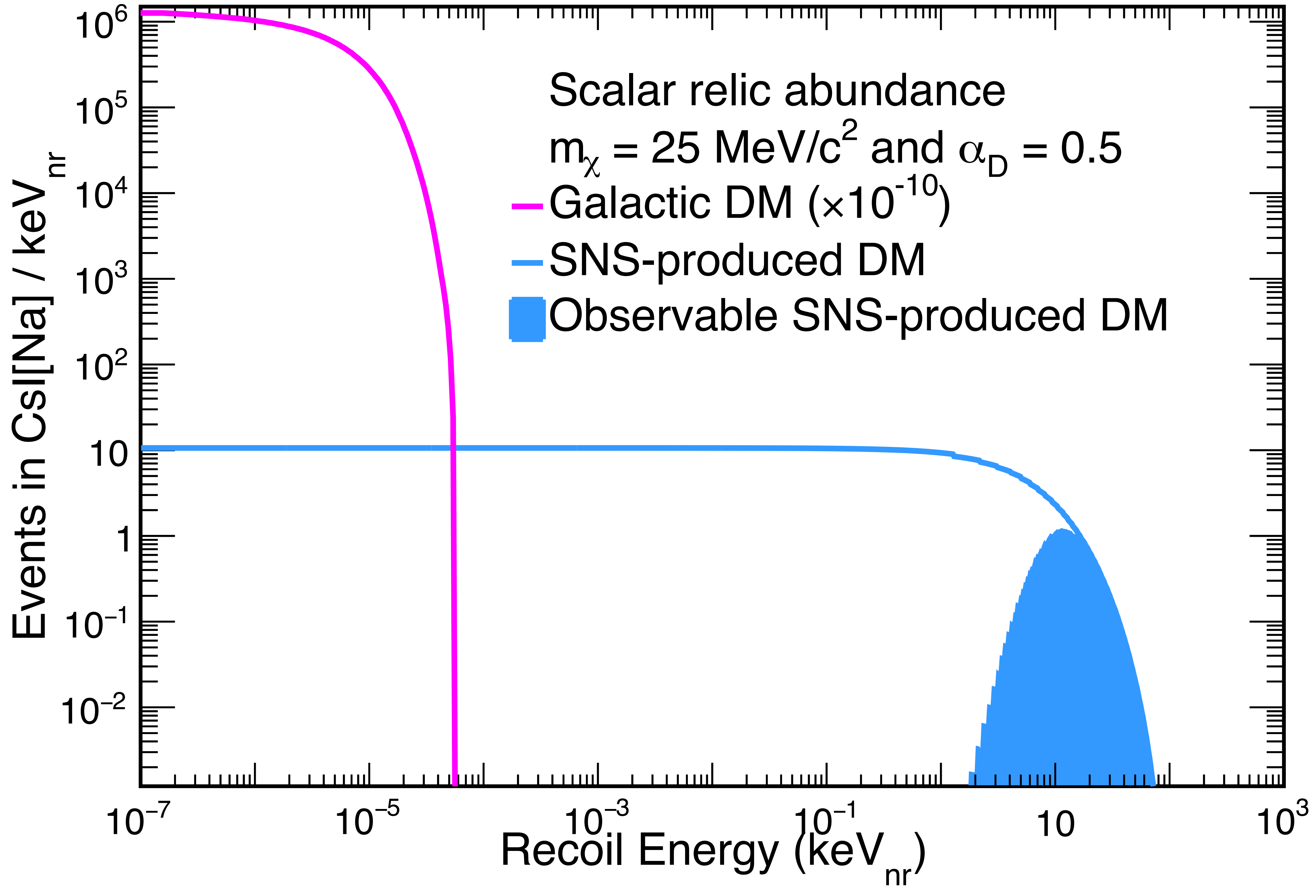


anomalous recoils from “CEDNS”

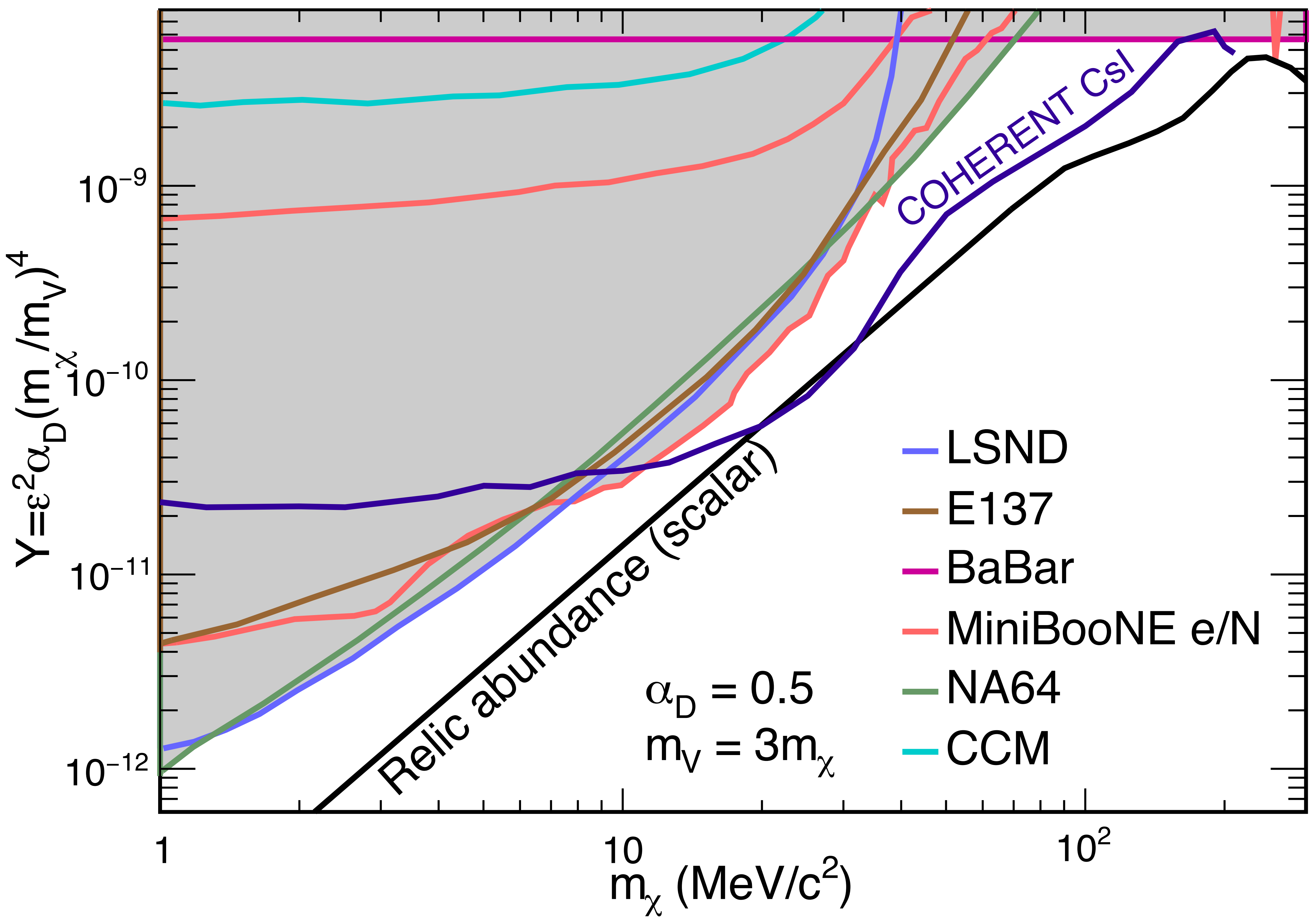


***CEDNS = DM version of CEvNS**

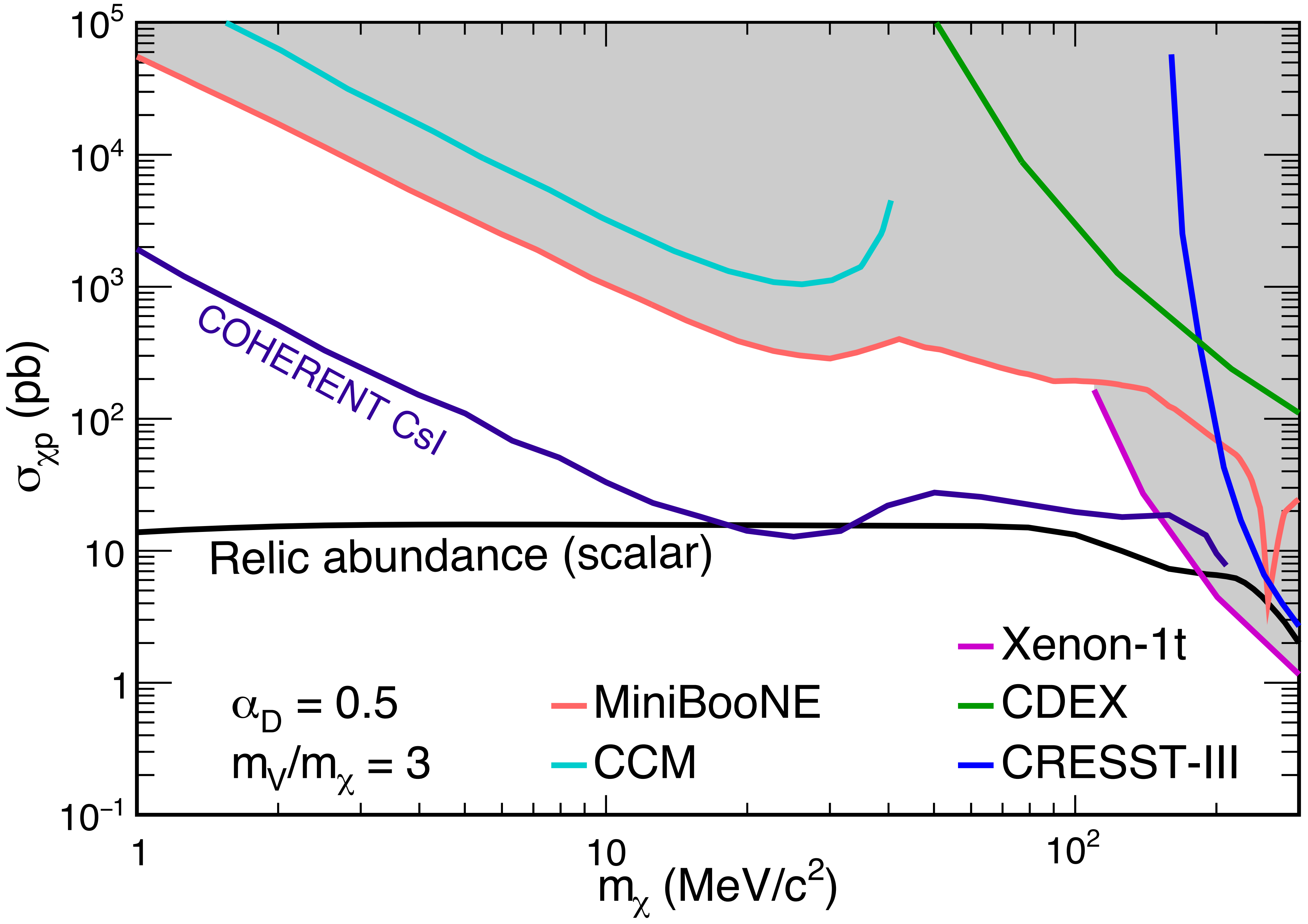
COHERENT collab [2110.11453]



Testing the Thermal Relic Hypothesis



Sensitivity to viable thermal relics!



CEvNS experiments can also play a leading role in DM direct detection

COHERENT Collaboration: Akimov et al., Phys. Rev. Lett. 130, 051803 – Published 3 February, 2023

More fun with CEvNS to come

Status and latest results from CONNIE with a skipper-CCD detector

Jun 11, 2025, 7:23 PM
23m
Great Hall

Parallel session presen… | Neutrino Masses, M… | Neutrino Masses. Mixi…

Speaker

Brenda Aurea Cervantes Vergara (Fermilab)

Descrip

The Cohere
the coherer
from the co
a ~40-gram
light media
detecting ir
energy thre
limits on CE
conducted
electron sca
charge of m
technology,
in 2024 to a
CONNIE ski

Search for Coherent Elastic Neutrino-Nucleus Scattering with the Ricochet Experiment

Jun 11, 2025, 8:09 PM
23m
Great Hall

Parallel session presen… | Neutrino Masses, M… | Neutrino Masses. Mixi…

Speaker

Emanuela Celi (Northwestern University)

Description

Since its discovery in 2017, interest in Coherent Elastic Neutrino-Nucleus Scattering (CENNS) has rapidly increased. The precise measurement of CENNS energy spectrum and cross section opens the possibility of exploring physics beyond the Standard Model and plays a crucial role in constraining the background for next-generation dark matter experiments.
Cryogenic detectors are particularly well-suited for observing CENNS due to their exceptional sensitivity, which allows for the detection of particle interactions at very low energy thresholds. With this motivation, the RICOCHET experiment aims to perform a precision measurement of the CENNS spectrum by detecting neutrinos emitted from the nuclear reactor at the Institut Laue–Langevin in France.
The experiment plans to employ an array of cryogenic thermal detectors using different technologies: germanium ionization and phonon detectors using Neutron Transmutation Doped (NTD) thermometers, and superconductor-based detectors using Transition Edge Sensor (TES) thermometers. In this talk, I will present an overview of the RICOCHET experiment and discuss its most recent results.

Status of the Scintillating Bubble Chamber Liquid Argon 10 kg (SBC-LAr10) Detector, and Future Neutrino Physics Prospects

Jun 11, 2025, 7:46 PM
23m
Great Hall

Parallel session presen… | Neutrino Masses, M… | Neutrino Masses. Mixi…

Speaker

Gray Putnam (Fermilab)

Description

The Scintillating Bubble Chamber (SBC) collaboration is developing liquid noble bubble chambers as a technology for the detection of low energy (sub-keV) nuclear recoils. Identifying recoils at this energy would enable searches for light (~GeV) dark matter, as well as the observation of coherent elastic neutrino nucleus scattering (CEvNS) at low neutrino energy (such as from a reactor source). The SBC-LAr10 detector at Fermilab, currently building towards its first physics run, will measure how a liquid argon bubble chamber responds to low energy nuclear recoils. These measurements will determine the precise energy threshold, resolution, and background rejection characteristics of the technology, answering questions that will enable its application to neutrino and dark matter physics. In this talk, I will introduce our progress towards operating the detector at Fermilab. I will discuss the program of measurements to be made at Fermilab. In addition to the detector physics, SBC-LAr10 has the potential to perform its own dark matter search, as well as observe GeV-scale neutrino-nucleus interactions in the Neutrinos at the Main Injector (NuMI) beam. Finally, I will highlight future prospects for making measurements of low energy neutrinos through CEvNS with the large detector volumes that scintillating bubble chambers have the potential to scale to.

CONNIE, SBC-LAr10, RICOCHET, MINER, COHERENT, Coherent CAPTAIN Mills coming up today/tomorrow

Conclusions

- CEvNS experimental program is multifaceted & rapidly expanding.
    - Offers powerful probe of a variety of new physics scenarios.
- On the **neutrino side**: NSI, neutrino EM properties, and sterile neutrinos.
- Can also be viewed as a DM factory, and test well-motivated ideas for **light DM**.

Extras